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**$\chi_{c1}$  and  $\chi_{c2}$  Resonance Parameters with the Decays  $\chi_{c1,c2} \rightarrow J/\psi \mu^+ \mu^-$** R. Aaij *et al.*\*

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The decays  $\chi_{c1} \rightarrow J/\psi \mu^+ \mu^-$  and  $\chi_{c2} \rightarrow J/\psi \mu^+ \mu^-$  are observed and used to study the resonance parameters of the  $\chi_{c1}$  and  $\chi_{c2}$  mesons. The masses of these states are measured to be  $m(\chi_{c1}) = 3510.71 \pm 0.04(\text{stat}) \pm 0.09(\text{syst})$  MeV and  $m(\chi_{c2}) = 3556.10 \pm 0.06(\text{stat}) \pm 0.11(\text{syst})$  MeV, where the knowledge of the momentum scale for charged particles dominates the systematic uncertainty. The momentum-scale uncertainties largely cancel in the mass difference  $m(\chi_{c2}) - m(\chi_{c1}) = 45.39 \pm 0.07(\text{stat}) \pm 0.03(\text{syst})$  MeV. The natural width of the  $\chi_{c2}$  meson is measured to be  $\Gamma(\chi_{c2}) = 2.10 \pm 0.20(\text{stat}) \pm 0.02(\text{syst})$  MeV. These results are in good agreement with and have comparable precision to the current world averages.

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Studies of the properties and production of quarkonia at hadron colliders provide an important testing ground for quantum chromodynamics [1]. Measurements of the spectra test potential models [2], while the production rate can be calculated perturbatively in nonrelativistic effective field theories such as nonrelativistic QCD [3]. Most studies of  $\chi_{c1}$  and  $\chi_{c2}$  mesons at hadron colliders have exploited the radiative decays  $\chi_{c1,c2} \rightarrow J/\psi \gamma$  with the subsequent decay  $J/\psi \rightarrow \mu^+ \mu^-$  [4–8]. The branching fractions for these processes are large, allowing a signal to be observed despite a high background.

Recently, the BESIII Collaboration [9] reported the first observation of the electromagnetic Dalitz decays [10] of  $\chi_{c0}$ ,  $\chi_{c1}$  and  $\chi_{c2}$  mesons into the  $J/\psi e^+ e^-$  final state. This Letter reports the first observation of the  $\chi_{c1} \rightarrow J/\psi \mu^+ \mu^-$  and  $\chi_{c2} \rightarrow J/\psi \mu^+ \mu^-$  decay modes, using  $J/\psi \rightarrow \mu^+ \mu^-$  decays. These decays are used to measure the  $\chi_{c1}$  and  $\chi_{c2}$  masses together with the  $\chi_{c2}$  natural width. The event topology with four muons in the final state provides a clean signature that is ideal for studies in hadron collisions.

This analysis uses the LHCb data set collected in  $pp$  collisions up to the end of 2016. The data collected at center of mass energies of 7 and 8 TeV correspond to integrated luminosities of 1 and 2 fb<sup>-1</sup> and are collectively referred to as run 1, while data collected at a center of mass energy of 13 TeV correspond to 1.9 fb<sup>-1</sup> and are referred to as run 2.

The LHCb detector is a single-arm spectrometer covering the pseudorapidity range  $2 < \eta < 5$ , described in detail in Refs. [11,12]. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector

[13], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes [14] placed downstream of the magnet. The tracking system measures the momentum of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV (natural units with  $c = \hbar = 1$  are used throughout this Letter). The momentum scale is calibrated using samples of  $J/\psi \rightarrow \mu^+ \mu^-$  and  $B^+ \rightarrow J/\psi K^+$  decays collected concurrently with the data sample used for this analysis [15–17]. The use of the large  $J/\psi$  data sample allows us to correct for variations of the momentum scale at the level of  $10^{-4}$  or less that occur over time, while the use of the  $B^+ \rightarrow J/\psi K^+$  decay allows the momentum scale to be determined as a function of the  $K^+$  kinematics. The procedure is validated using samples of  $K_S^0 \rightarrow \pi^+ \pi^-$ ,  $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$ ,  $\psi(2S) \rightarrow \mu^+ \mu^-$ , and other fully reconstructed  $b$ -hadron and  $\Upsilon(nS)$ ,  $n = 1, 2, 3$ , decays. Based upon these studies, the accuracy of the procedure is evaluated to be  $3 \times 10^{-4}$ . Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [18]. The online event selection is performed by a trigger [19], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. The events used in this analysis are selected by a hardware trigger that requires one or two muons with transverse momentum  $p_T$ , larger than 1.5 GeV. At the software trigger stage, a pair of oppositely charged muons with an invariant mass consistent with the known  $J/\psi$  mass [20] is required. In run 1, the full event information for selected events was stored. To keep the rate within the available bandwidth, it was necessary to require  $p_T(J/\psi) > 3$  GeV. For run 2, a new data-taking scheme was introduced [21] allowing real-time alignment to be performed in the trigger [22] that, together with an increase in the online computing resources, made possible the full

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track reconstruction in the online system [23,24]. Consequently, lower-level information could be discarded, reducing the event size and allowing all events selected at the hardware stage that contain a  $J/\psi$  candidate to be stored without any  $p_T$  requirement.

Offline,  $J/\psi$  candidates are combined with a pair of oppositely charged muons to form  $\chi_{c1,c2} \rightarrow J/\psi \mu^+ \mu^-$  candidates. Several criteria are applied to reduce the background and maximize the sensitivity for the mass measurement. Selected muon candidates are required to be within the range  $2 < \eta < 4.9$ . Misreconstructed tracks are suppressed by the use of a neural network trained to discriminate between these and real particles. Muon candidates are selected with a neural network trained using simulated samples to discriminate muons from hadrons and electrons. Finally, to improve the mass resolution, a kinematic fit is performed [25]. In this fit, the mass of the  $J/\psi$  candidate is constrained to the known mass of the  $J/\psi$  meson [20], and the position of the  $\chi_{c1,c2}$  candidate decay vertex is constrained to be the same as that of the primary vertex. The  $\chi^2$  per degree of freedom of this fit is required to be less than four, which substantially reduces the background while retaining almost all the signal events.

In the simulation,  $pp$  collisions are generated using PYTHIA [26] with a specific LHCb configuration [27]. For this study, signal decays are generated using EVTGEN [28] with decay amplitudes that depend on the invariant dimuon mass  $m(\mu^+ \mu^-)$ , using the model described in Ref. [29]. This model assumes that the decay proceeds via the emission of a virtual photon from a pointlike meson and is known to provide a good description of the corresponding dielectron mode [9]. Final-state radiation is accounted for using PHOTOS [30]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [31] as described in Ref. [32].

The signal yields and parameters of the  $\chi_{c1,c2}$  resonances are determined with an extended unbinned maximum likelihood fit performed to the  $J/\psi \mu^+ \mu^-$  invariant mass distribution. In this fit, the  $\chi_{c1}$  and  $\chi_{c2}$  signals are modeled by relativistic Breit-Wigner functions with Blatt-Weisskopf form factors [33] with a meson radius parameter of  $3 \text{ GeV}^{-1}$ . Jackson form factors [34] are considered as an alternative to estimate the uncertainty associated with this choice. The orbital angular momentum between the  $J/\psi$  meson and the  $\mu^+ \mu^-$  pair is assumed to be 0 (1) for the  $\chi_{c1}$  ( $\chi_{c2}$ ) cases.

The relativistic Breit-Wigner functions are convolved with the detector resolution. Three resolution models are found to describe the simulated data well: a double-Gaussian function, a double-sided Crystal Ball function [35,36], and a symmetric variant of the Apollonios function [37]. The double-Gaussian function is used by the default model, and the other functions are considered to estimate the systematic uncertainty. The parameters of the resolution model are determined by a simultaneous fit to the  $\chi_{c1}$  and

$\chi_{c2}$  simulated samples. All the parameters apart from the core resolution parameter  $\sigma$  are common between the two decay modes. For all the models in the simulation, it is found that  $\alpha \equiv \sigma^{\chi_{c2}} / \sigma^{\chi_{c1}} = 1.13 \pm 0.01$ . This is close to the value expected,  $\alpha = 1.11$ , from the assumption that the resolution scales with the square root of the energy release.

The combinatorial background is modeled by a second-order polynomial function. The total fit function consists of the sum of the background and the  $\chi_{c1}$  and  $\chi_{c2}$  signals. The free parameters are the yields of the two signal components, the yield of the background component, the two background shape parameters, the  $\chi_{c1}$  and  $\chi_{c2}$  masses,  $\sigma^{\chi_{c1}}$ , and the natural width of the  $\chi_{c2}$  resonance,  $\Gamma(\chi_{c2})$ . The other resolution parameters are fixed to the simulation values. Since the natural width of the  $\chi_{c1}$  state  $\Gamma(\chi_{c1}) = 0.84 \pm 0.04 \text{ MeV}$  [20] is less than the detector resolution ( $\sigma^{\chi_{c1}} = 1.41 \pm 0.01 \text{ MeV}$ ), this study has limited sensitivity to its value. By applying Gaussian constraints on the natural width of the  $\chi_{c1}$  state (to the value from Ref. [20]) and  $\alpha$  (to the value found in the simulation), the  $\chi_{c2}$  width is determined in a data-driven way using the observed resolution for the  $\chi_{c1}$  state.

The fit of this model to the full data sample is shown in Fig. 1, and the resulting parameters of interest are summarized in Table I. The fitted value of  $\sigma^{\chi_{c1}}$  is  $1.51 \pm 0.04 \text{ MeV}$ , which agrees at the level of 5% with the value found in the simulation. Figure 2 shows the  $m(\mu^+ \mu^-)$  mass distribution for selected candidates where the background has been subtracted using the *sPlot* technique [38]. The data agree well with the model described in Ref. [29].

The dominant source of systematic uncertainty on the mass measurements comes from the knowledge of the

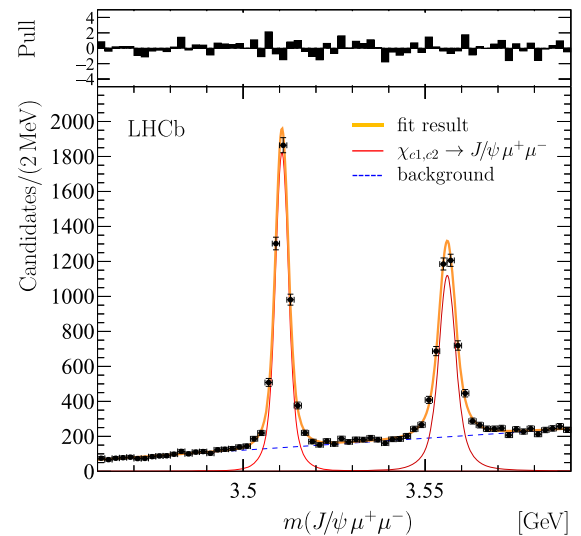


FIG. 1. Mass distribution for selected  $J/\psi \mu^+ \mu^-$  candidates. The fit is shown in thick orange, the  $\chi_{c1}$  and  $\chi_{c2}$  signal components by the thin red solid curve, and the background component by the dashed blue curve.

TABLE I. Signal yields and resonance parameters from the nominal fit. No correction for final-state radiation is applied to the mass measurements at this stage.

Fit parameter	Fitted value
$N(\chi_{c1})$	$4755 \pm 81$
$N(\chi_{c2})$	$3969 \pm 96$
$m(\chi_{c1})$ [MeV]	$3510.66 \pm 0.04$
$m(\chi_{c2})$ [MeV]	$3556.07 \pm 0.06$
$\Gamma(\chi_{c2})$ [MeV]	$2.10 \pm 0.20$

momentum scale. This is evaluated by adjusting the momentum scale by the  $3 \times 10^{-4}$  uncertainty on the calibration procedure and rerunning the mass fit. Uncertainties of 88 and 102 keV are assigned to the  $\chi_{c1}$  and  $\chi_{c2}$  mass measurements, respectively. A further uncertainty arises from the knowledge of the correction for energy loss in the spectrometer, which is known with 10% accuracy [12]. Based on the studies in Ref. [17], a 20 keV uncertainty is assigned.

The distortion of the line shape due to final-state radiation introduces a bias on the mass. This bias is evaluated using the simulation to be  $47 \pm 7$  keV ( $29 \pm 10$  keV) for the  $\chi_{c1}$  ( $\chi_{c2}$ ) where the uncertainty is statistical. The central values of the mass measurements are corrected accordingly, and the uncertainties are propagated.

Other uncertainties arise from the fit modeling and are studied using a simplified simulation. Several variations of the relativistic Breit-Wigner distribution are considered. Using Jackson form factors, modifying the meson radius parameter, and varying the orbital angular momentum, the observed  $\chi_{c1}$  ( $\chi_{c2}$ ) mass changes by at most 15 (24) keV, which is assigned as a systematic uncertainty. Similarly, fitting with a double-sided Crystal Ball or Apollonios

model, variations of 7 and 2 keV are seen for the  $\chi_{c1}$  and  $\chi_{c2}$  masses, respectively, and assigned as systematic uncertainties. Finally, varying the order of the polynomial background function results in a further uncertainty of 2 keV. The uncertainties due to the momentum scale and energy loss correction largely cancel in the mass difference. The assigned systematic uncertainties on the mass measurements are summarized in Table II.

The main uncertainty on the determination of the natural width of the  $\chi_{c2}$  is due to the knowledge of the detector resolution. This is accounted for in the statistical uncertainty, since the resolution scale is determined using the  $\chi_{c1}$  signal in the data. Similarly, the uncertainty on the knowledge of the  $\chi_{c1}$  width is propagated via the Gaussian constraint in the mass fit. By running fits with and without the constraint, the latter is evaluated to be 40 keV. Further uncertainties of 10 and 20 keV arise from the assumed Breit-Wigner parameters and resolution model, respectively. Other systematic uncertainties, e.g., due to the background model, are negligible. The stability of the results is studied by dividing the data into different running periods and also into kinematic bins and repeating the fit. None of these tests shows evidence of a systematic bias.

In summary, the decays  $\chi_{c1} \rightarrow J/\psi \mu^+ \mu^-$  and  $\chi_{c2} \rightarrow J/\psi \mu^+ \mu^-$  are observed and the mass of the  $\chi_{c1}$  meson together with the mass and natural width of the  $\chi_{c2}$  are measured. The results for the mass measurements are

$$m(\chi_{c1}) = 3510.71 \pm 0.04 \pm 0.09 \text{ MeV},$$

$$m(\chi_{c2}) = 3556.10 \pm 0.06 \pm 0.11 \text{ MeV},$$

$$m(\chi_{c2}) - m(\chi_{c1}) = 45.39 \pm 0.07 \pm 0.03 \text{ MeV},$$

where the first uncertainty is statistical and the second is systematic. The dominant systematic uncertainty is due to the knowledge of the momentum scale and largely cancels in the mass difference. It can be seen in Table III that the measurements are in good agreement with and have comparable precision to the best previous ones, made using  $p\bar{p}$  annihilation at the threshold by the E760 [39] and E835 experiments [40] at Fermilab. They are considerably more precise than the best measurement based on the

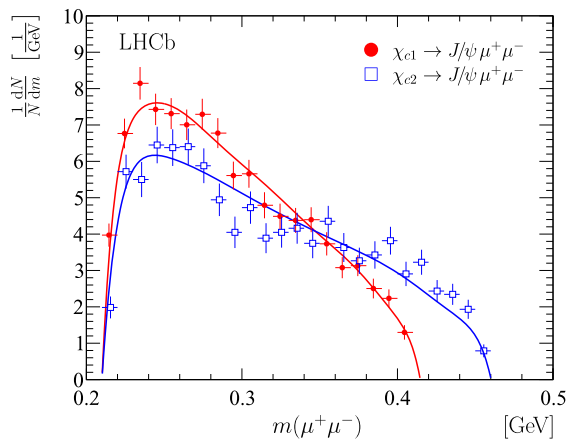


FIG. 2. Background-subtracted  $m(\mu^+ \mu^-)$  distribution for  $\chi_{c1} \rightarrow J/\psi \mu^+ \mu^-$  (solid red circles) and  $\chi_{c2} \rightarrow J/\psi \mu^+ \mu^-$  (open blue squares) decays. The distributions are normalized to the unit area. The curves show the expected distribution from the simulation, which uses the model described in Ref. [29].

TABLE II. Systematic uncertainties (in keV) on the mass and mass difference measurements.

Source of uncertainty	$m(\chi_{c1})$	$m(\chi_{c2})$	$m(\chi_{c2}) - m(\chi_{c1})$
Momentum scale	88	102	18
Energy loss correction	20	20	...
Final-state radiation	7	10	12
Resonance shape	15	24	25
Background model	<2	<2	<2
Resolution model	7	2	6
Sum in quadrature	92	107	34



TABLE III. LHCb measurements, compared to both previous measurements from Ref. [39] and the current world averages from Ref. [20]. The quoted uncertainties includes statistical and systematic uncertainties.

Quantity [MeV]	LHCb measurement	Best previous measurement	World average
$m(\chi_{c1})$	$3510.71 \pm 0.10$	$3510.72 \pm 0.05$	$3510.66 \pm 0.07$
$m(\chi_{c2})$	$3556.10 \pm 0.13$	$3556.16 \pm 0.12$	$3556.20 \pm 0.09$
$\Gamma(\chi_{c2})$	$2.10 \pm 0.20$	$1.92 \pm 0.19$	$1.93 \pm 0.11$

final-state reconstruction [41]. It should be noted that the world average for the  $\chi_{c1}$  mass has a scale factor of 1.5 to account for the poor agreement between the results [20]. The result for the  $\chi_{c2}$  natural width is

$$\Gamma(\chi_{c2}) = 2.10 \pm 0.20(\text{stat}) \pm 0.02(\text{syst}) \text{ MeV}.$$

It has similar precision to and is in good agreement with previous measurements [20].

The observations presented here open up a new avenue for hadron spectroscopy at the LHC. These decay modes can be used to measure the production of  $\chi_{c1}$  and  $\chi_{c2}$  states with a similar precision to the converted photon study presented in Ref. [6]. Importantly, it will be possible to extend measurements down to very low  $p_T(\chi_{c1,c2})$  probing further QCD predictions [42–44]. In addition, measurements of the transition form factors [45] will provide input on the interaction between charmonium states and the electromagnetic field. With larger data samples, studies of the Dalitz decays of other heavy-flavor states will become possible. For example, the measurement of the transition form factor of the  $X(3872)$  via its Dalitz decay may help elucidate the nature of this enigmatic state [9].

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